Bellcomm/V Muenmat
→ Fm file (vsm) OCT 2 1 1968
Route to DRA
DFO

68-FM-227

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MSC INTERNAL NOTE NO. 68-FM-227

September 20, 1968

affects m/c correction req.?

NOV 3 1969 NOT ENOUGH to be CONCERNED ABOUT

EFFECTS OF WATER BOILER VENTING ON THE APOLLO 6 MISSION

Technical Library, Bellcomm, Inc.

RECEIVED FEB 1975 NASA STI FACILITY INPUT BRANCH

Mathematical Physics Branch

MISSION PLANNING AND ANALYSIS DIVISION

MANNED SPACECRAFT CENTER

HOUSTON, TEXAS

(NASA-TM-X-72380) EFFECTS OF WATER BOILER VENTING ON THE APOLLO 6 MISSION (NASA) 24 p

N75-72103

Unclas
00/98 17650

MSC INTERNAL NOTE NO. 68-FM-227

PROJECT APOLLO

EFFECTS OF WATER BOILER VENTING ON THE APOLLO 6 MISSION

By Richard K. Osburn
Mathematical Physics Branch

September 20, 1968

MISSION PLANNING AND ANALYSIS DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

Approved: _____
James C. McPherson, Chief
Mathematical Physics Branch

Approved: _____
John P. Mayer, Chief
Mission Planning and Analysis Division

CONTENTS

Section	Page
SUMMARY	1
INTRODUCTION	1
ANALYSIS	2
RESULTS	4
CONCLUSIONS	5
APPENDIX - DEFINITION OF THE JPL COORDINATE SYSTEM	6

FIGURES

Figure		Page
1	USB tracking coverage	10
2	Ascension Doppler residuals for a Doppler-only fit	11
3	Carnarvon Doppler residuals for a Doppler-only fit	12
4	Guam Doppler residuals for a Doppler-only fit	13
5	Ascension Doppler residuals based on the C-band trajectory	14
6	Carnarvon Doppler residuals based on the C-band trajectory	15
7	Ascension Doppler residuals based on considering an unknown venting	16
8	Carnarvon Doppler residuals based on considering an unknown venting	17
9	Guam Doppler residuals based on considering an unknown venting	18
10	Difference in the RSS positions computed with and without an unknown venting	19
11	Difference in the RSS velocity computed with and without an unknown venting	20

EFFECTS OF WATER BOILER VENTING ON THE APOLLO 6 MISSION

By Richard K. Osburn

SUMMARY

Unexpected perturbations in the Apollo 6 trajectory were noted in both real-time and postflight orbit determination efforts. The trend noted in the unified S-band (USB) Doppler data indicated the presence of unmodeled trajectory perturbations and led to the postulation of spacecraft venting as a possible cause. A clue was provided by those involved in postflight analysis of the reaction control subsystem (RCS), who believed that the environmental control subsystem (ECS) water boiler had helped to create an asymmetrical RCS duty cycle. Initial calculations confirmed that the water boiler could have accounted for the trajectory differences noted. Subsequent runs at the Jet Propulsion Laboratory (JPL) utilizing the JPL Surveyor orbit determination program provided conclusive evidence that the trajectory perturbations were due to water boiler venting. Further analysis showed that similar venting could create significant problems in future missions.

INTRODUCTION

The purpose of this paper is to present the results of an analysis of the effects of water boiler venting on the Apollo 6 coast ellipse trajectory. Preflight analyses by North American Rockwell (NAR or, formally, North American Aviation, Inc.) had concluded that the thrust created by the boil-off would not perturb the vehicle trajectory. Postflight analyses, however, indicated that the water boiler contributed significantly to the unpredicted perturbations noted in the trajectory. The magnitude of deviations noted in the Apollo 6 trajectory was such that similar errors in transearth orbit determination might result in a miss of the reentry corridor. Thus, the need to pinpoint the cause of the problem became readily apparent.

Due to limitations on the in-house orbit determination programs, the JPL Surveyor orbit determination program was used for several significant portions of the trajectory analysis. A feature of the program allows an unknown low-thrust perturbation to be included in the solution vector. The acceleration due to the unknown thrust is solved for in an inertially fixed coordinate system. Since the CSM was oriented in an inertial attitude (cold soak) during the coast ellipse, this option was useful in determining

the magnitude of the venting force.

ANALYSIS

Figure 1 is a bar chart summarizing USB tracking data received during the Apollo 6 coast ellipse. The Ascension data drop-out at 15^h58^m (G.m.t.) was the result of the Ascension computer going down. This situation was corrected at 16^h19^m. Postflight analysis determined that all USB data received were valid.

The first symptoms of the water boiler venting were encountered when the Real-Time Computer Complex (RTCC) found it necessary to significantly downweight the a priori information in order to obtain a satisfactory fit of Carnarvon USB data during the down-leg of the coast ellipse. Similar problems were encountered postflight when an attempt was made to fit all coast ellipse data in a single segment.

Figures 2 through 4 are the residual[a] plots for a Doppler-only fit of all coast phase data. The waveforms noticeable in the residual plots were not expected, as the 1σ noise and bias values for Doppler data are 0.09 Hz and 0.14 Hz, respectively. Attempts made to minimize the residuals included solving for errors in station location, timing, and the earth's gravitational constant (μ). None of these succeeded in producing an acceptable fit to the data. To obtain an independent estimate of the data quality, a vector from the C-band best estimate of the trajectory (BET) was passed through the USB Doppler data. Figures 5 and 6 are the Ascension and Carnarvon Doppler residuals based on the C-band trajectory. Of interest is the deviation of the Carnarvon Doppler residuals after 19 hours G.m.t. At this point it became necessary to examine the data used in obtaining the C-band vector. During the Apollo 6 mission the C-band transponder on the CSM was shut down near apogee as an attempt to solve a hardware problem. The problem persisted, but the beacon was not turned back on. Consequently, the C-band BET was based only upon data prior to apogee. Possible explanations for the problem now became more readily apparent. The deviation in the Carnarvon residuals is characteristic of an unmodeled thrust perturbing the trajectory. The least-squares differential corrector, in attempting to minimize the residuals, hides the problem when the entire tracking arc is fit. However, when shorter

---

[a]Residuals are obtained by considering a given data point, computing the values of the observables based on the propagated epoch-vector, and obtaining the difference in the observed and computed values.

portions are fit, an accurate estimate of the trajectory is obtained for the short arc. In passing a vector obtained in this manner (i.e., the C-band BET vector) through the remaining data the nature of the problem is revealed.

Two possibilities were investigated to determine the cause of the suspected thrusting. These were uncoupled RCS thrusting and unmodeled spacecraft venting. A check revealed that all RCS thrusters were nominally operative during the mission. This eliminated the first possibility. It was learned, however, that the RCS duty cycle necessary to hold the spacecraft in the cold soak attitude had been highly asymmetrical, with two negative pitch firings for each positive firing. Assuming that the suspected thrust was not actually oriented through the spacecraft center of gravity, this was also a symptom of spacecraft venting. The water boiler vent had been postulated as a possible cause of the asymmetrical duty cycle, so this was the first source of venting investigated.

In examining postflight data from the Apollo 4 mission, it was found that the pressure in the water boiler had been 0.15 lb/in^2. The diameter of the circular orifice was 2.5 in. Thus, from F = PA (where F is force, P is pressure, and A is area), the force at the vent is found to be 0.74 lb. Assuming a worst-case direction for the force (i.e., directed along the velocity vector) at all times, and using $\Delta V \approx at = \frac{Ft}{m}$ (where a is acceleration, t is time, and m is mass) to obtain an estimate of the ΔV imparted to the trajectory, the velocity change is found as follows:

$$F = 0.74 \text{ lb}$$

$$t = 6 \text{ hr}$$

$$m \approx 1000 \text{ slugs}$$

And thus: $\Delta V \approx 16$ fps.

The value of 16 fps is a very crude approximation to the actual change in velocity which would result from a force of 0.74 lb. To obtain an accurate estimate, the expression $\frac{\partial V_F}{\partial V(t)} (\Delta V)$ (where V_F is the final velocity and ΔV is the instantaneous change of velocity) must be integrated over the 6 hours of the coast ellipse. This proceeds as follows:

Instantaneous ΔV = a = acceleration

a = constant for water boiler

$$\Delta V = \int_{t_1}^{t_2} \frac{\partial V_F}{\partial V(t)} a \, dt = a \int_{t_1}^{t_2} \frac{\partial V_F}{\partial V} dt$$

For an Apollo 6 coast phase trajectory,

$$\int_{t_1}^{t_2} \frac{\partial V_F}{\partial V} dt > (t_2 - t_1) a$$

Hence, $\Delta V > a(t_2 - t_1)$, and 16 fps is a conservative estimate of the actual velocity perturbation which would result at reentry from a force of 0.74 lb acting throughout the coast phase.

The maximum Doppler shift noted in the residuals of figure 6 is 17 Hz. This corresponds to a velocity change of 3.5 fps, and thus the perturbations noted in the trajectory are well within the possible effects of the water boiler.

The water boiler vent had now been postulated as a possible cause of the trajectory perturbations noted in Apollo 6 data. However, a method of proving the theory was needed. Examination of in-house and TRW programs revealed that software limitations prevented any positive action from being undertaken. It was finally decided to fit the data by using the JPL Surveyor orbit determination program. This program provides the user with an option to solve for an unknown, low-thrust acceleration in an inertial coordinate system. (Note that the cold-soak attitude with the CSM maintained during the coast ellipse approximates an inertial attitude.) The runs desired were made at JPL and the results returned to MSC.

RESULTS

The JPL Surveyor orbit determination program solved for an acceleration of 0.3411×10^{-7} km/sec^2. At this time the weight of the spacecraft was 25 376 lb. Then the vent force, from F = ma, was 0.089 lb. A determination of the direction of the solved-for venting force was somewhat more complicated. The system in which the JPL program solved for the acceleration was based on the sun-vehicle and Canopus-vehicle vectors. Several transformations were necessary in order to transform the direction of the solved-for vector into the Apollo CM spacecraft coordinate system. The appendix defines the JPL coordinate system and presents in detail the steps necessary to transform the JPL acceleration vector into the required Apollo coordinates.

When considering the significance of the magnitude and direction of the solved-for force, remember that the only elements of the solution vector were the vehicle state (three components of position and velocity) and the three components of the acceleration vector. The least-squares processor attempts to account for all deviations by varying the solution vector elements. Consequently, the solved-for acceleration possibly includes effects of other errors such as station location and timing, and uncertainities in the earth potential model. It is thus reasonable to assume that the acceleration obtained by the program would not correspond exactly with the acceleration due to the water boiler vent.

The results of the analysis showed that 87 percent of the solved-for acceleration was directed along the water boiler vent. This corresponded to a venting force of 0.077 lb. Postflight analysis by NAR had previously determined that the average force due to water boiler venting during the coast ellipse was 0.08 ± .019 lb. Figures 7 through 9 present the Doppler residuals for Ascension, Carnarvon, and Guam based on the JPL trajectory. These may be compared with figures 2 through 4 to note the improvement caused by solving for the unknown acceleration. Of additional interest are the differences between the trajectories with and without the solved-for acceleration. Figures 10 and 11 are time plots of the root-sum-square (RSS) differences in position and velocity, respectively, for the two trajectories.

CONCLUSIONS

Both the magnitude and direction of the venting force obtained by the JPL program were in excellent agreement with postflight data provided by NAR. In addition, consideration of the venting acceleration in the solution vector produced nominal residual patterns, while state-only solutions were unable to provide a nominal fit of the coast ellipse data. These facts lead directly to a conclusion that the water boiler was the main source of significant trajectory perturbation noted in Apollo 6 data by both the RTCC and postflight analysis. We may also conclude, by noting the differences between two trajectories, one of which did not consider the venting force, that the low thrust (0.08 lb) may have very serious effects on orbit determination results.

APPENDIX

DEFINITION OF THE JPL COORDINATE SYSTEM

Let

$\bar{U}_{SP}$ = unit vector along sun-vehicle line, directed away from sun

$\bar{E}$ = unit vector along Canopus-vehicle line, directed away from Canopus

$\bar{N} = \bar{E} \times \bar{U}_{SP}$

$\bar{T} = \bar{N} \times \bar{U}_{SP}$

$$\begin{bmatrix} \bar{T}^* \\ \bar{N}^* \end{bmatrix} = \begin{bmatrix} \cos K & \sin K \\ -\sin K & \cos K \end{bmatrix} \begin{bmatrix} \bar{T} \\ \bar{N} \end{bmatrix}$$

Components of the unknown acceleration were solved for by the JPL program in the ($\bar{U}_{SP}$, $\bar{T}^*$, $\bar{N}^*$) system. The acceleration was then defined as follows:

$$\bar{F} = f_1 \bar{U}_{SP} + f_2 \bar{T}^* + f_3 \bar{N}^*$$

where f_1, f_2, and f_3 are the solved-for components.

The resulting acceleration vector was transformed into the Apollo Block I CSM coordinate system by the following operations:

The $\bar{U}_{SP}$ and $\bar{E}$ vectors were obtained in an earth-centered inertial true-of-date coordinate system.

$$\bar{U}_{SP} = \begin{bmatrix} -0.96625 \\ -0.23634 \\ -0.10250 \end{bmatrix} \qquad E = \begin{bmatrix} 0.06132 \\ -0.60320 \\ 0.79523 \end{bmatrix}$$

Then we have

$$\bar{N} = \bar{E} \times \bar{U}_{SP} = \begin{bmatrix} 0.24977 \\ -0.76211 \\ -0.59733 \end{bmatrix}$$

$$\bar{T} = \bar{N} \times \bar{U}_{SP} = \begin{bmatrix} -0.06306 \\ 0.60277 \\ -0.79542 \end{bmatrix}$$

For the particular JPL program used to obtain the solution $K \approx 30^\circ$

$$\begin{bmatrix} \bar{T}^* \\ \bar{N}^* \end{bmatrix} = \begin{bmatrix} \cos 30^\circ & \sin 30^\circ \\ -\sin 30^\circ & \cos 30^\circ \end{bmatrix} \begin{bmatrix} \bar{T} \\ \bar{N} \end{bmatrix}$$

$$\bar{T}^* = \begin{bmatrix} 0.07027 \\ 0.14096 \\ -0.98752 \end{bmatrix}$$

$$\bar{N}^* = \begin{bmatrix} 0.24784 \\ -0.96139 \\ -0.11960 \end{bmatrix}$$

The JPL program solved for the following components of acceleration:

$$\begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix} = 10^{-7} \begin{bmatrix} 0.00531 \\ -0.13793 \\ 0.31199 \end{bmatrix} \quad \text{km/sec}^2$$

$$\bar{r} = f_1 \bar{U}_{SP} + f_2 \bar{T}^* + f_3 \bar{N}^*$$

Thus, in the earth-centered inertial system:

$$\bar{r} = (10^{-7}) \begin{bmatrix} 0.06250 \\ -0.32064 \\ 0.09835 \end{bmatrix}$$

This vector must now be transformed into the Apollo Block I CSM coordinate system. Let $\ddot{\bar{R}}$ be the acceleration vector in the spacecraft system.

Then:

$$\ddot{\bar{R}} = ABR\,\bar{f}$$

$$\text{where } A = \begin{bmatrix} \cos 33^\circ & 0 & \sin 33^\circ \\ 0 & 1 & 0 \\ -\sin 33^\circ & 0 & \cos 33^\circ \end{bmatrix}$$

$$B = \begin{bmatrix} \cos M \cos I & \sin M & -\cos M \sin I \\ \sin O \sin I - \cos O \sin M \cos I & \cos O \cos M & \cos O \sin M \sin I + \sin O \cos I \\ \sin O \sin M \cos I + \cos O \sin I & -\sin O \cos M & \cos O \cos I - \sin O \sin M \sin I \end{bmatrix}$$

M = MGA = Middle Gimbal Angle
I = IGA = Inner Gimbal Angle
O = OGA = Outer Gimbal Angle
R = REFSMMAT

For the high ellipse cold-soak attitude of the Apollo 6 mission the gimbal angles and RESFMMAT were as follows:

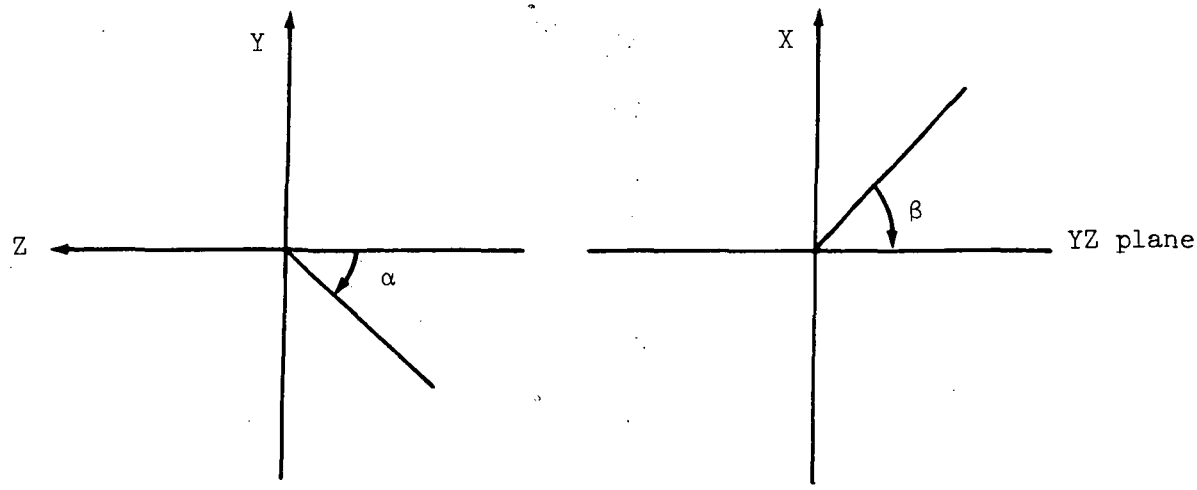
MGA = 359.22°
OGA = 58.04°
IGA = 160.97°

$$\text{REFSMMAT} = \begin{bmatrix} -0.33265 & -0.81245 & 0.47882 \\ 0.45853 & -0.30434 & -0.83494 \\ 0.82407 & 0.49730 & 0.27129 \end{bmatrix}$$

After performing the required transformations we obtain:

$$\ddot{\bar{R}} = \begin{bmatrix} -0.17539 \\ 0.16611 \\ 0.18157 \end{bmatrix}$$

The direction of the water boiler vent must now be determined in the CSM coordinate system. The vent position and direction are described in the following diagrams:



$$\alpha = 13.05^\circ$$

$$\beta = 28.25^\circ$$

From these diagrams the following direction cosines for the direction of the water boiler thrust are defined:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} -0.47332 \\ 0.22580 \\ 0.97417 \end{bmatrix}$$

The thrust vector obtained from postflight analysis of the data defined the following directional cosines:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} -0.58039 \\ 0.54969 \\ 0.60085 \end{bmatrix}$$

The orientation angles α and β would then be as follows:

$$\alpha = 41.95^\circ$$

$$\beta = 35^\circ 41' = 35.70^\circ$$

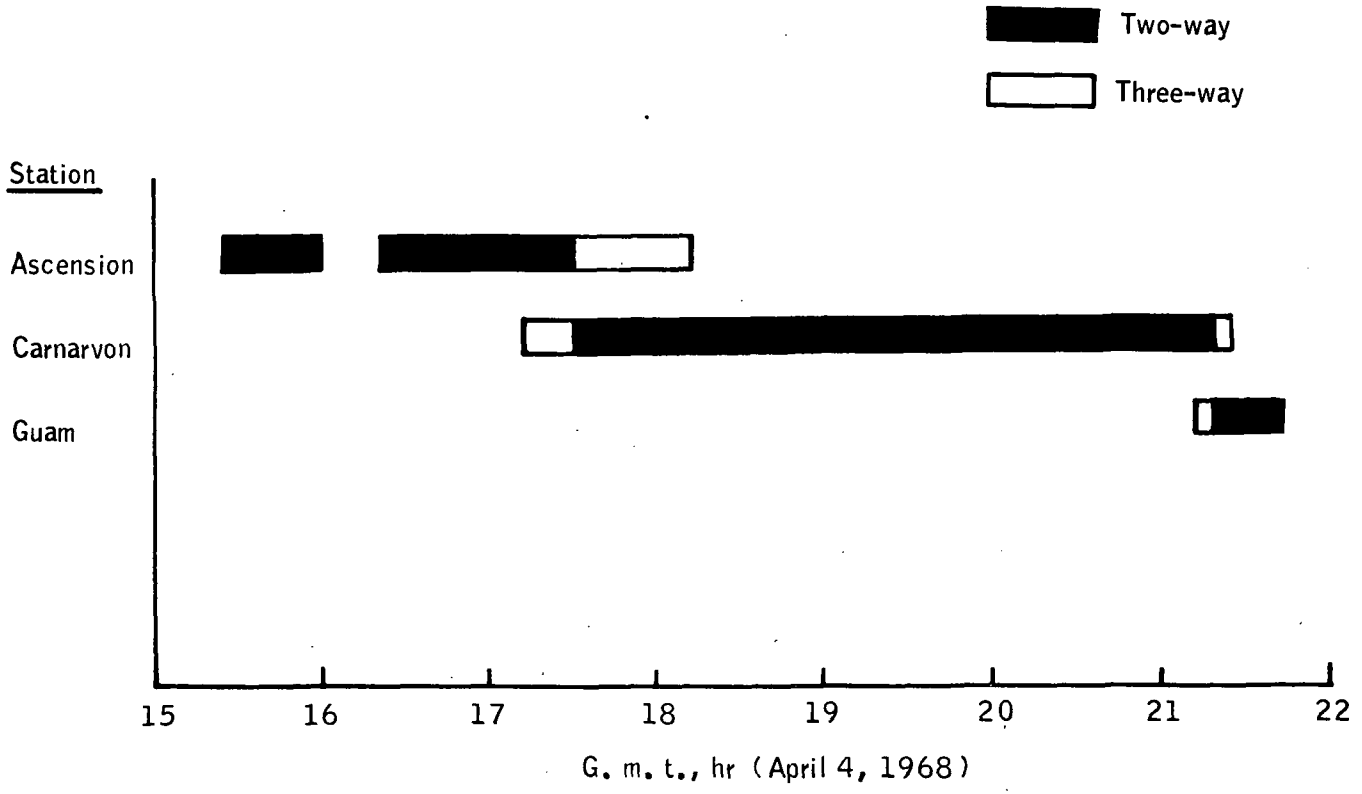


Figure 1.- USB tracking coverage.

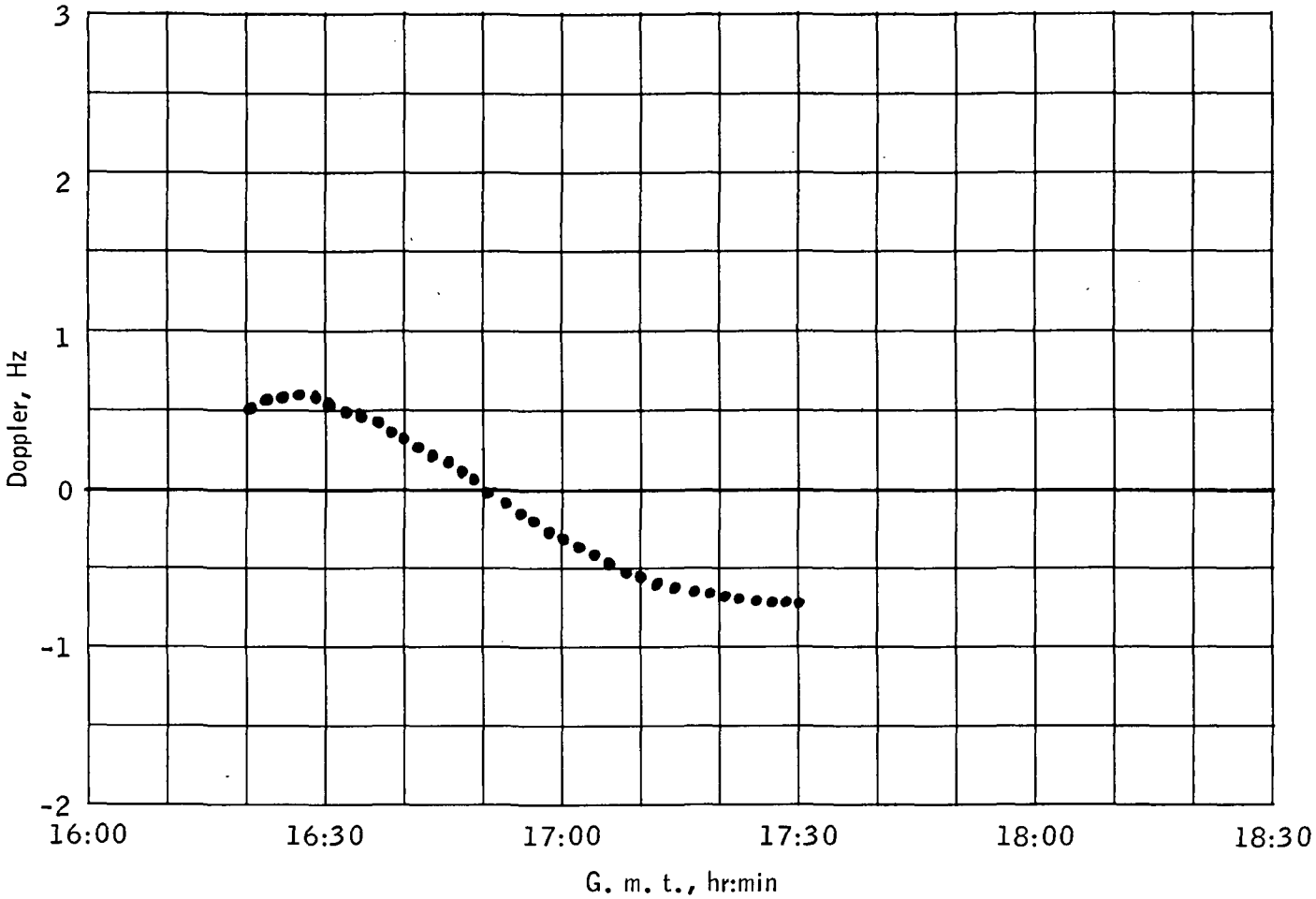


Figure 2.- Ascension Doppler residuals for a Doppler-only fit.

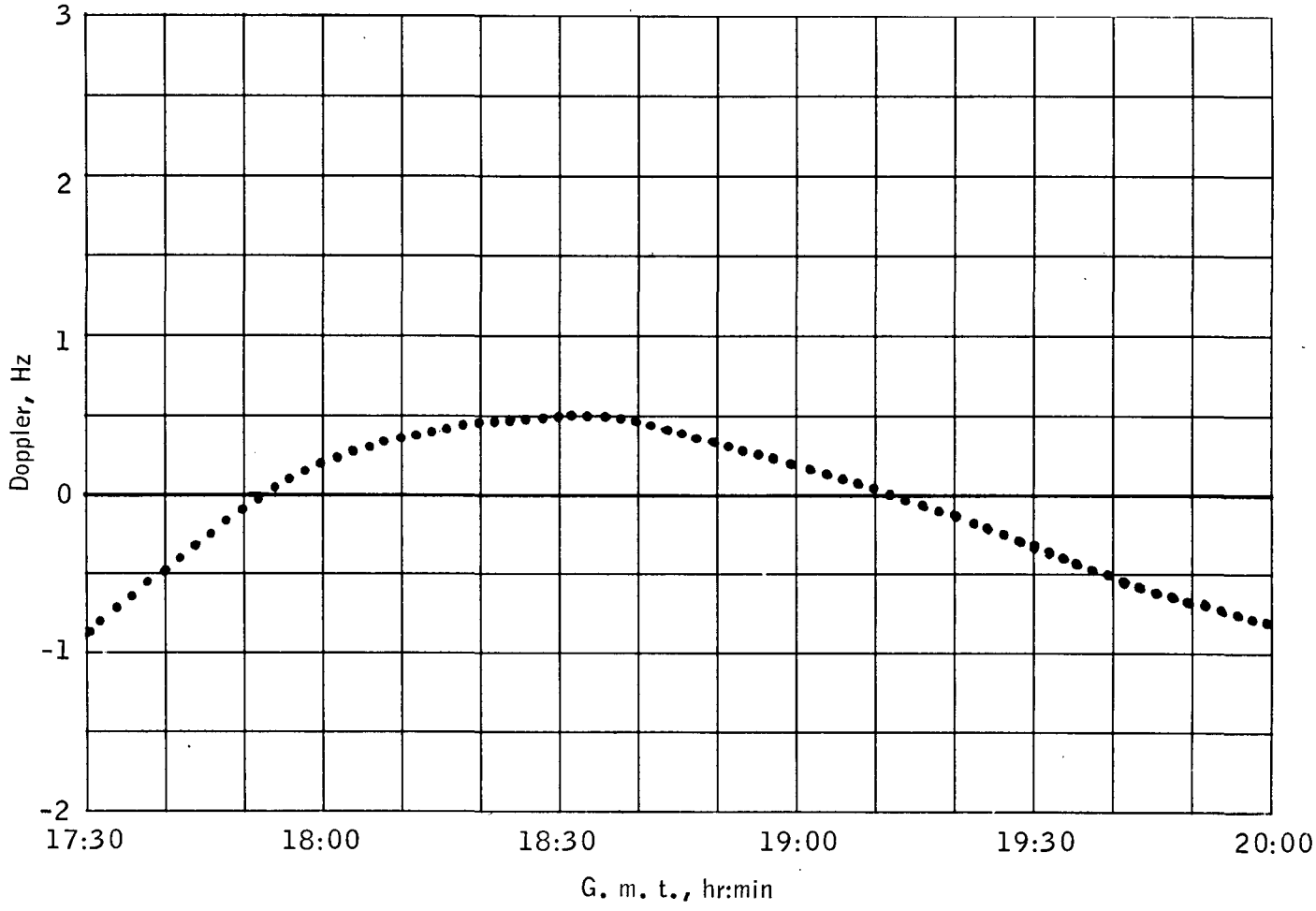


Figure 3.- Carnarvon Doppler residuals for a Doppler-only fit.

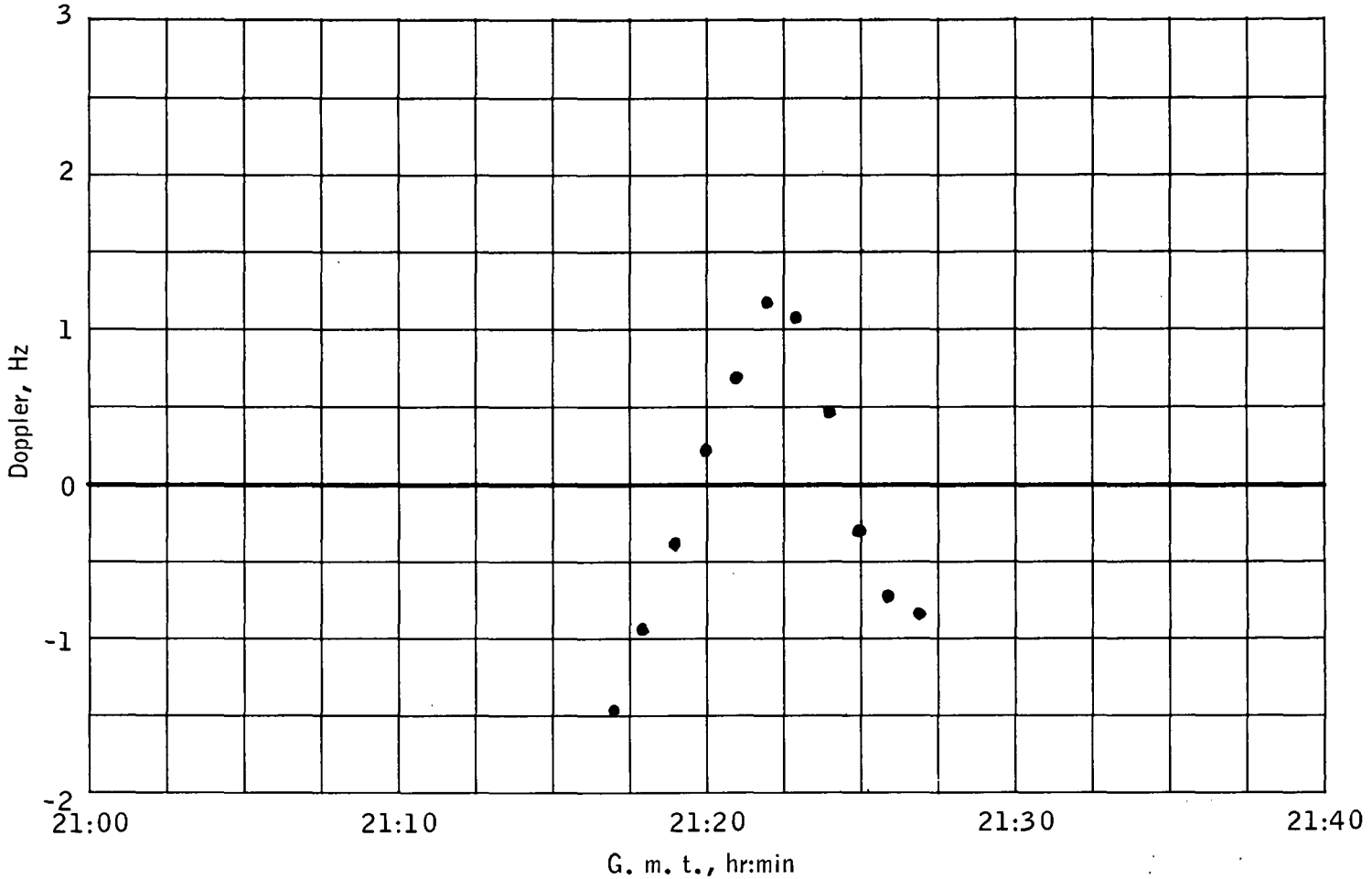


Figure 4.- Guam Doppler residuals for a Doppler-only fit.

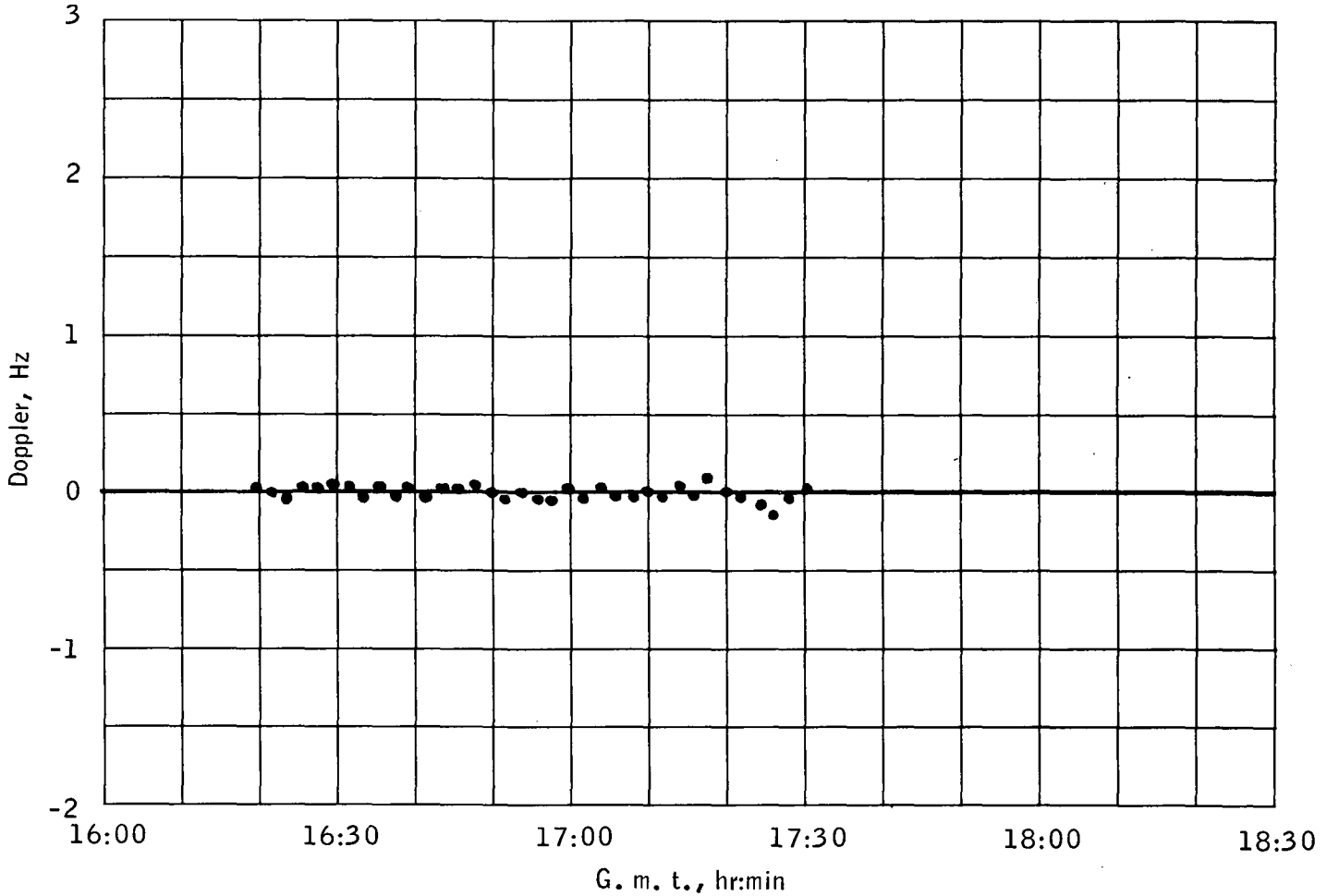


Figure 5.- Ascension Doppler residuals based on the C-band trajectory.

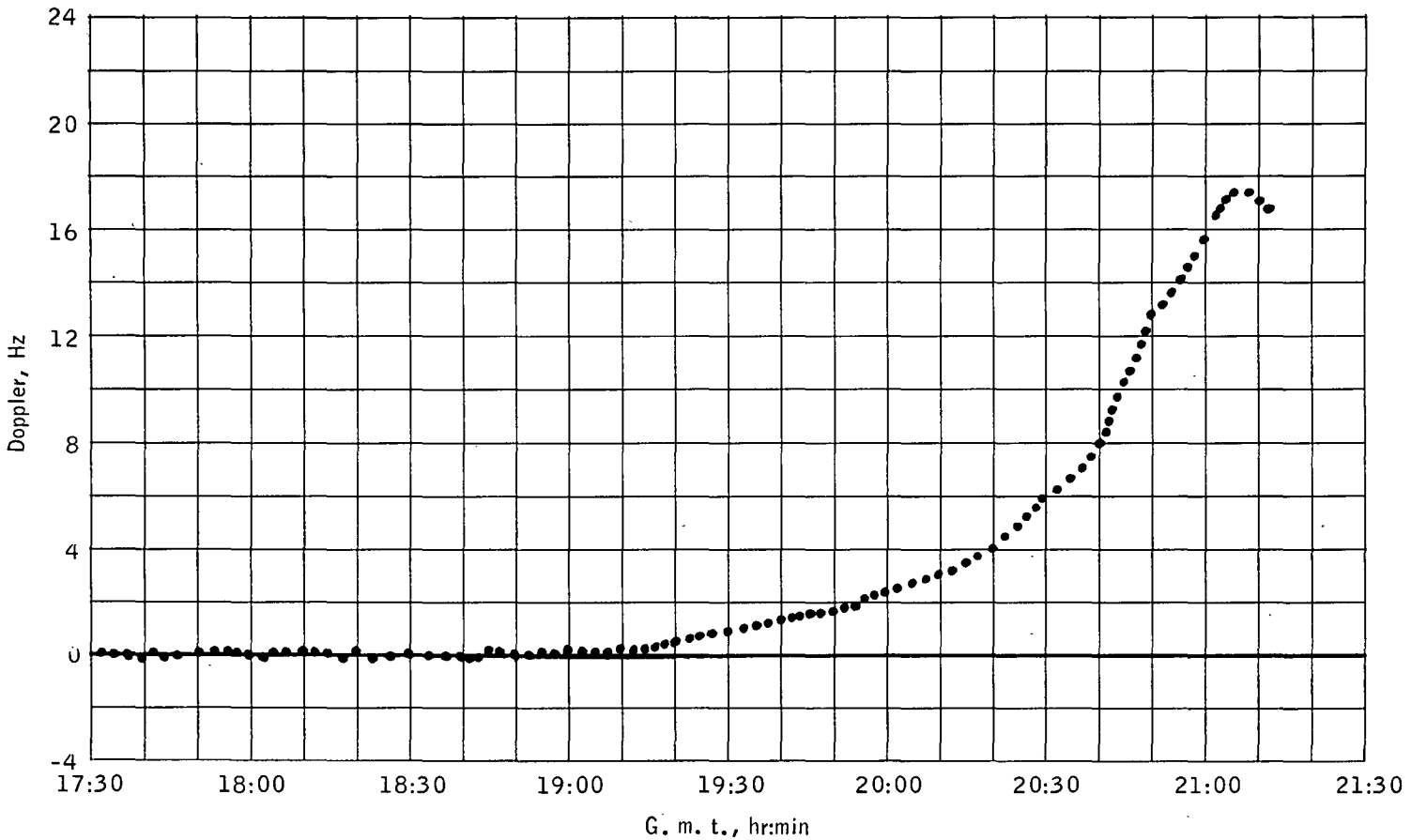


Figure 6.- Carnarvon Doppler residuals based on the C-band trajectory.

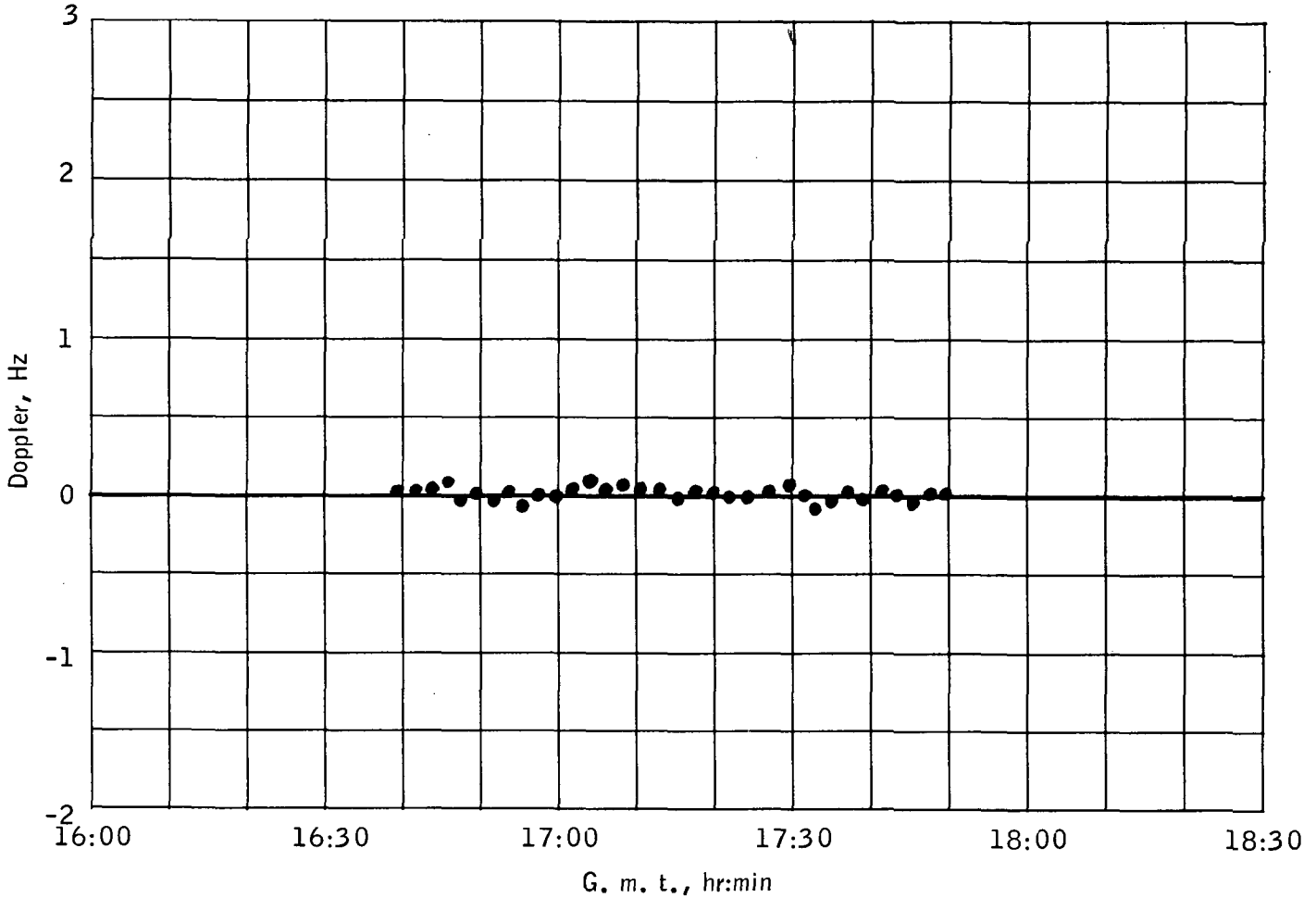


Figure 7.- Ascension Doppler residuals based on considering an unknown venting.

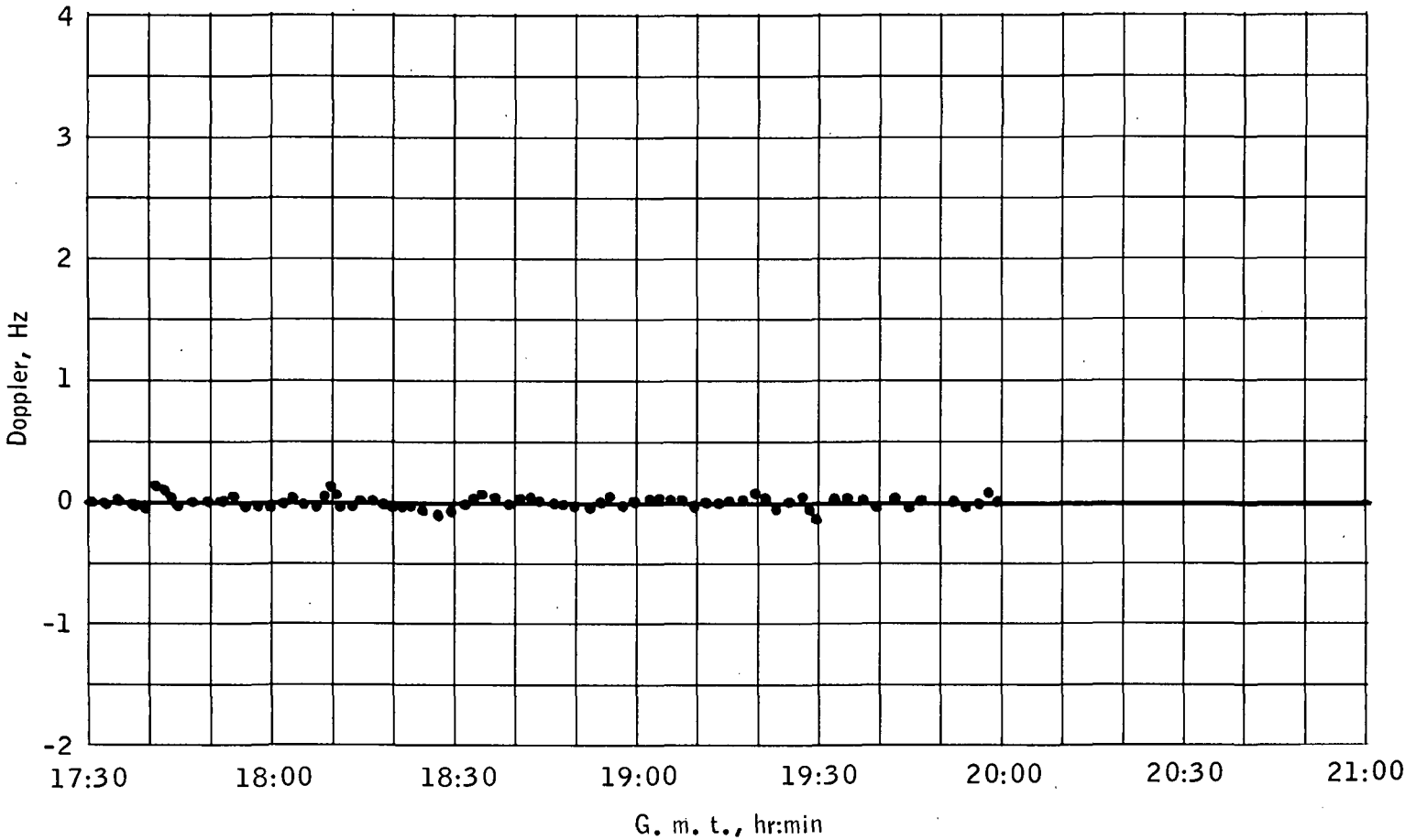


Figure 8.- Carnarvon Doppler residuals based on considering an unknown venting.

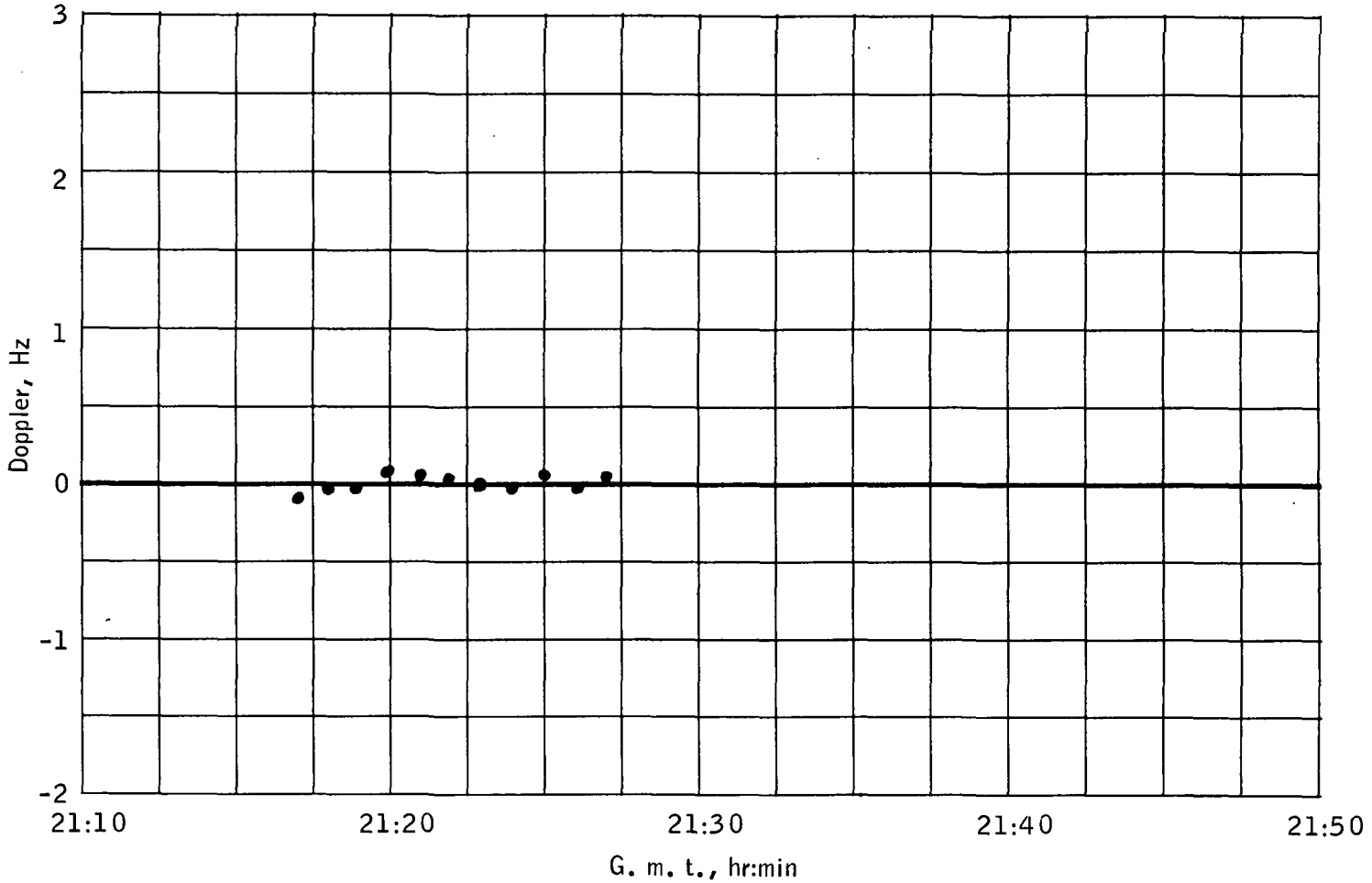


Figure 9.- Guam Doppler residuals based on considering an unknown venting.

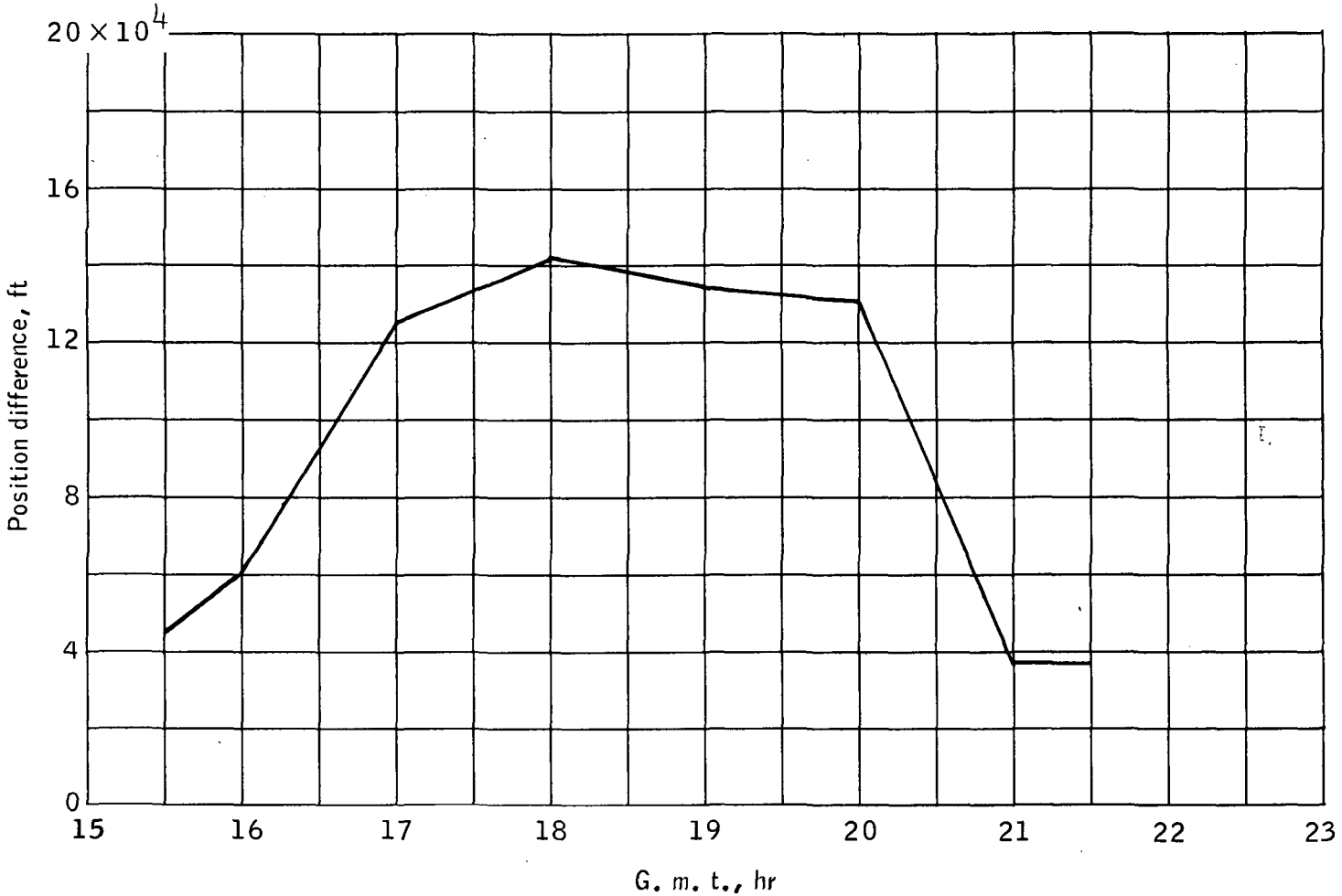


Figure 10.- Difference in the RSS positions computed with and without an unknown venting.

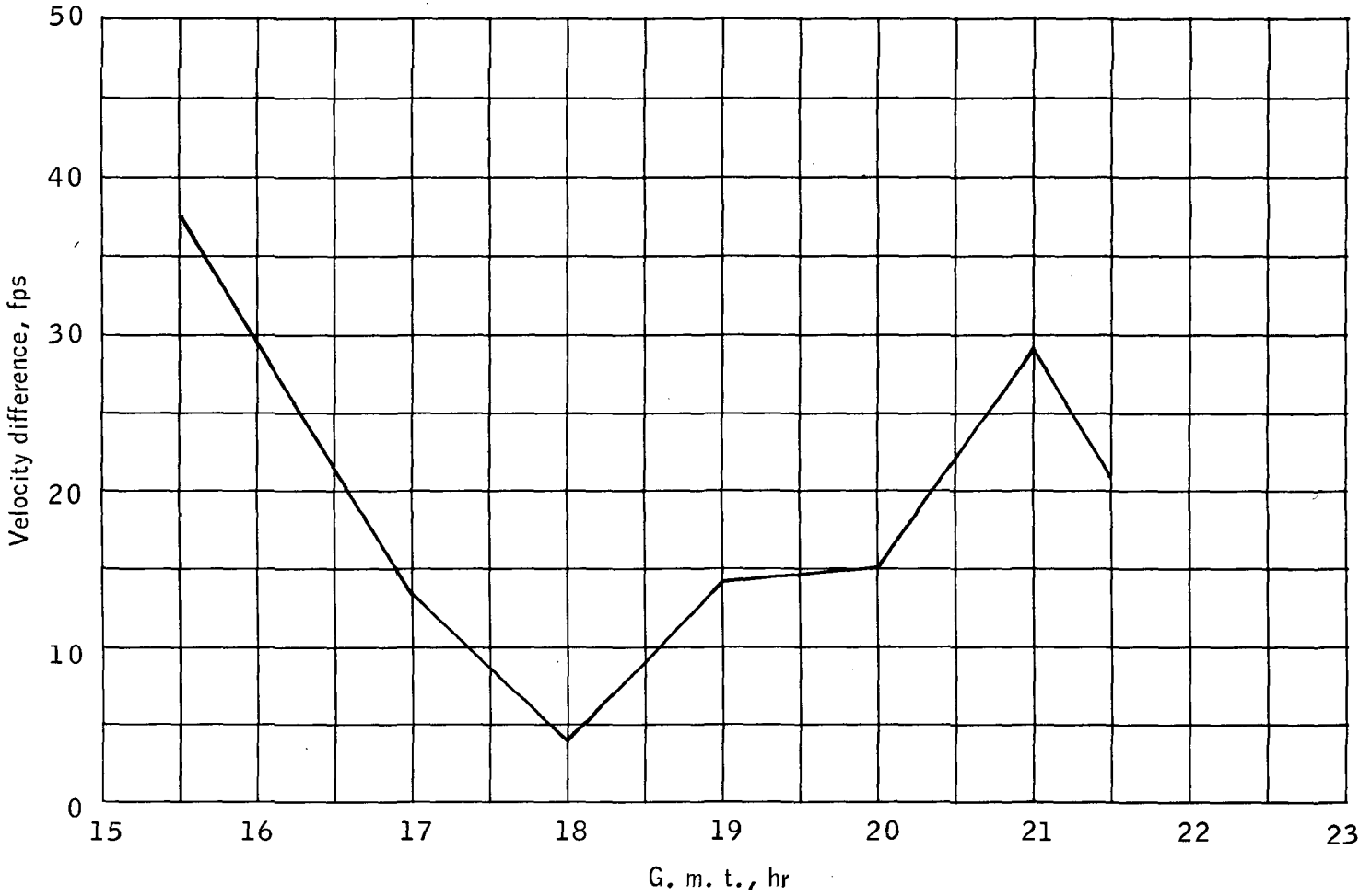


Figure 11.- Difference in the RSS velocity computed with and without an unknown venting.